Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

June 17, 2022

RF Accelerator Technology R&D

Report of AF7-rf Topical Group to Snowmass 2021

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Executive Summary

Accelerator radio frequency (RF) technology has been and remains critical for modern high energy physics (HEP) experiments based on particle accelerators. Tremendous progress in advancing this technology has been achieved over the past decade in several areas highlighted in this report. These achievements and new results expected from continued R&D efforts could pave the way for upgrades of existing facilities, improvements to accelerators already under construction (e.g., PIP-II), well-developed proposals (e.g., ILC, CLIC) and/or enable concepts under development, such as FCC-ee, CEPC, C^3, HELEN, multi-MW Fermilab Proton Intensity Upgrade, future Muon Colloder, etc. Advances in RF technology have impact beyond HEP on accelerators built for nuclear physics, basic energy sciences and other areas. Recent examples of such accelerators are European XFEL, LCLS-II and LCLS-II-HE, SHINE, SNS, ESS, FRIB and EIC. To support and enable new accelerator-based applications and even make some of them feasible, we must continue addressing their challenges via a comprehensive RF R&D program that would advance the existing RF technologies and explore the nascent ones.

The ongoing RF technology R&D efforts closely follow the decadal roadmap that was developed in the framework of the DOE General Accelerator R&D (GARD) program in 2017 [1]. The roadmap reflects the most promising research directions that can potentially enable future experimental HEP programs. Similar to the DOE GARD roadmap, the European particle physics community developed a roadmap for European accelerator R&D presented in a report, which includes a roadmap for high-gradient RF structures and systems [2]. The two roadmaps cover similar RF technology topics thus presenting opportunities for collaboration between the U.S. and European institutions.

Here we highlight recent progress in selected key RF technology areas.

Main breakthroughs in the **Superconducting RF (SRF) cavity performance** were in the area of developing advanced surface treatments. Following the discovery of nitrogen doping about 10 years ago, it was further developed and quickly adopted for SRF cavities of LCLS-II. This success triggered world-wide collaboration on studying different surface treatments and resulted in several new treatment recipes, including variants of nitrogen doping for LCLS-II-HE and PIP-II, mid-temperature treatment, nitrogen infusion, and 2-step low-temperature treatment. Further experimental and theoretical research is needed to fully understand physics of RF superconductivity in the thin surface layer. This understanding would allow precisely tune treatment recipes to specific accelerator applications. However, in the medium accelerating gradient range (15 to 25 MV/m), already developed recipes have an impact on the performance of prototype SRF cavities for PIP-II and CEPC and further developments will impact FCC-ee, multi-MW Fermilab Proton Intensity Upgrade, and possibly a muon collider. For machines that are proposed to operate at higher gradients, new recipes, e.g., 2-step baking, will push the cavity performance to 55–60 MV/m in standing wave structures and to $\sim$ 70 MV/m and beyond in traveling wave SRF structures. This would enable future upgrades of the ILC or a new, more compact, SRF linear collider HELEN. In combination with other cost saving measures under development – medium grade niobium material, novel high-efficiency RF sources, advanced resonance control, etc. – the proposed SRF R&D program would make future HEP facilities more affordable.

On a longer R&D time scale, it is very important to continue studies of advanced thin film technologies and innovative materials for SRF cavity applications. The most advanced of such materials is Nb_3Sn. The superheating field of Nb_3Sn corresponds to a maximum accelerating gradient of approximately 100 MV/m (for standing wave structures), well above that of niobium. Even with very limited investments in this material so far, the best Nb_3Sn cavities can already reach $\sim$ 25 MV/m. Also, having a critical temperature about twice of the niobium critical temperature, Nb_3Sn can operate at temperatures $\sim$ 4.5 K while maintaining high quality factors, thus offering significant capital and operational savings on cryogenic systems. Beyond Nb and Nb_3Sn, several other superconducting materials and advanced thin film technologies are being investigated.

The most notable development in the **high-gradient normal conducting RF** area is novel parallel-coupled C-band structures operating at liquid nitrogen temperature for the recently proposed C^3 collider and other applications. The highly optimized cell shape of the standing wave structure and increased electrical conductivity of copper at 80 K result in significantly improved shunt impedance and hence reduced RF power. The lower thermal stresses in the material and improved material strength reduce probability of breakdown, allowing to design the collider with an accelerating gradient of 120 MV/m. Prototype one-meter structures have been fabricated and tested at high gradient and at cryogenic temperatures. The next step is to develop an HOM damped and detuned structure design to mitigate the effect of the long-range wakefields in C^3.

Optimization of cavity design, temperature, frequency and material properties has also allowed for the operation of structures with a gradient in excess of 200 MV/m, and cavities with a shunt impedances of a GΩ/m. The powering of these structures with novel high-efficiency RF sources, which have also made significant progress, is opening new frontiers in beam brightness, beam manipulation, diagnostics, and acceleration.

Structure Wakefield Acceleration (SWFA), one of the advanced accelerator concepts, uses high-charge drive beam to excite intense wakefield in a structure. Then these wakefield accelerate a low-charge main beam. Use of short pulses of $\sim$ 10 ns (more than an order of magnitude shorter than those typically used in pulsed high-power klystrons) in SWFA structures could mitigate RF breakdown and result in higher gradients, exceeding 150 MV/m and perhaps reaching 300 MV/m. Much progress has been made in recent years in developing dielectric structures (including dielectric tubes, dielectric slabs and dielectric disk-loaded structures) and metallic periodic structures in both X-band and in the millimeter wave band. Structures with novel topologies, such as metamaterial structures, photonic bandgap structures and photonic topological crystals, have been tested successfully.

RF systems and sources power and control the beams that we deliver for HEP experiments and are a significant portion of the facility infrastructure. Dedicated efforts to improve peak power, average power and efficiency have shown remarkable progress on all fronts with the adoption of new beam bunching techniques, new manufacturing techniques and multi-beam devices. New concepts for RF components from cavity tuners to windows to pulse compressors continue to improve the power levels and efficiency we deliver RF power to accelerators. Importantly, the overall RF system performance does not only rely on power and efficiency, but also on precision and stability. Modern controls and low level RF (LLRF) electronics have made tremendous progress with RF phase and amplitude stability, fast feedback, and beam positioning. Combined with real time AI/ML controls significant improvements in beam brightness and luminosity are within reach.

Discussion about **Innovative Design and Modeling** highlighted aspects of high current and high brightness sources, bright beams and wakefields, accelerator modeling, and some cavity R&D issues. The exchange between a number of key experts triggered the writing of several Snowmass White Papers. A Beam and Accelerator Modeling Interest Group (BAMIG) was formed, consisting of 25 key players from 13 U.S. laboratories and Universities. The common Snowmass White Paper emphasizes the importance of computational tools for the critical design, commissioning, operation, and upgrading of accelerator facilities.

Most advanced and often sophisticated high-performance computing tools are required to support R&D activities. Efforts in code writing are often local and somewhat uncoordinated which leads to duplication, to non-exiting interoperability, to challenges with respect to sustainability, and to the simultaneous retirement of codes and code owner. The need for advanced simulation studies, the long-term support for code development and maintenance, strengthening of collaborative efforts among laboratories and universities, the enabling of 'virtual prototyping' of accelerator components, the improvement of real-time simulations, – all this is recognized as vital for new accelerator development. In the White Paper modeling needs are summarized according to the fields of RF-based acceleration, plasma- and structure-based wakefield acceleration, PetaVolts per meter plasmonics and plasmonic acceleration, materials modeling for accelerator design, structured plasmas, and superconducting magnets. The author team describes each field and lists important references. Sustainability, reliability, user support and training are addressed. The path towards a community ecosystem is sketched. A Center for Accelerator and Beam Physics Modeling is proposed, and the envisaged activities are listed.

While the GARD roadmap continues to serve as a community-developed guidance for the RF technology R&D, it would benefit from some mid-course corrections. Based on the discussions and submitted White Papers, we present the following key directions that should be pursued during the next decade:

- Studies to push performance niobium and improve our understanding of SRF losses and ultimate quench fields via experimental and theoretical investigations;
- Developing methods for nano-engineering the niobium surface layer and tailoring SRF cavity performance to a specific application, e.g., a linear collider, a circular collider, or a high-intensity proton linac;
- Investigations of new SRF materials beyond niobium via advanced deposition techniques and bringing these materials to practical applications;
- Developing advanced SRF cavity geometries to push accelerating gradients of bulk niobium cavities to ~ 70 MV/m for either upgrade of the ILC or compact SRF linear collider;
- Pursuing R&D on companion RF technologies to mitigate field emission, provide precise resonance control, etc.;
- Research on application of SRF technology to dark sector searches;
- R&D on high-gradient normal conducting RF structures operating at cryogenic temperatures with a gradient of > 150 MV/m as a promising way toward a compact linear collider;
- R&D on high frequency and multi-frequency structures to transcend limits on shunt impedance and accelerating gradients;
- Investigation of novel materials and manufacturing techniques to improve high gradient performance and remove design constraints;
- Developing high efficiency, low-cost RF sources that would benefit many operating and practically every future intensity or energy frontier machine;
- Studies dedicated to industrialization and cost reduction of fabricating RF components and systems;
- Continue research on advanced SWFA structures to bring them closer to practical applications;
- Experimental and theoretical research to further our understanding of the RF breakdown physics;

- Continued development of computational tools for multi-physics and virtual prototyping;
- Developing a community ecosystem for accelerator and beam physics modeling that would incorporate comprehensive set of high-performance simulation tools for RF-based accelerators.

To support these key research directions, there is a need to upgrade the existing or build new facilities that have the capabilities to test these new concepts and help integrate them into systems with ready access to researchers. Collaborative efforts at National Laboratories and universities have provided a broad spectrum of sources and manufacturing facilities that has enabled this progress. However, much of this infrastructure is aging and in need of rejuvenation. Without adequate investment in the facilities, further progress in advancing RF technologies will be hindered.